Quarterly Progress Report

Technical and Financial

Deep Water Ocean Acoustics
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Technical Progress Report

1. Introduction

The goal of this research is to increase our understanding of the impact of the ocean and seafloor environmental variability on deep-water (long-range) ocean acoustic propagation and to develop methodologies for including this in acoustic models. Experimental analysis is combined with model development to isolate specific physics and improve our understanding. During the past few years, the physics effects studied have been three-dimensional propagation on global scales, deep water ambient noise, under-ice scattering, bathymetric diffraction and the application of the ocean acoustic Parabolic Equation to infrasound.

2. Tasks

a. Task 1: Basin Scale Acoustics and CTBTO Data Analysis

Scenario

The scenario chosen to evaluate the impact of mesoscale variability on the arrival angle of long-range signals is a seismic event on the Kerguelen Plateau (-53°S 71°E) in the southern ocean. This region of the world, which includes Heard Island, Crozet Island and the Kerguelen Plateau has historical significance in the long-range underwater community (Perth-Bermuda, HIFT) and is the position of the IMS hydro-acoustic station HA04. As demonstrated in the Heard Island Feasibility Test, sound sources here can be detected from the Southern Atlantic to the Pacific. The receiver position is taken be approximately at the IMS HA10S location (Ascension Island southern station). The hydroacoustic station at Ascension, as can be seen in Figure 1, has acoustic visibility to the South Atlantic, South Indian and South Pacific and has a large number of hydroacoustic signals generated by seismic events.

Results

Many of these results were reported in the previous July 15 Quarterly Progress Report. During this period of Performance the complete simulation time series was finished and the final back-azimuth versus year-day and frequency curve was generated.

The beamformer output was collapsed to a single back-azimuth value by computing the centroid of the beam power over the searched arrival angle. The time-series of the back-azimuth for the set of model simulations is shown Figure 1, along with the geodesic back-azimuth. There is substantially more deflection observed in the ECCO2 result than in the WOA09 result, indicating that the combined impact of the mesoscale eddies and sharper front definition is important to the acoustic propagation path. There is a long time-scale oscillation on the order of a 120-day period, ostensibly related to seasons, but it does not repeat for each season of 1992 to the corresponding season of 1993. This oscillation leads to the range in the back-azimuths going from a minimum near 141.5° to a maximum of 143.1°. The back-azimuth as a function of frequency does show coherent behavior, at least within the observed 0.3° small time scale variability. There is one outlier in the data. The July 28th, 1993 results exhibit a split arrival for 2, 4 and 8 Hz. This is evident faintly in Figure 1. This double arrival leads to a significant change to the centroid computation. There is a consistent 3-6 day oscillation in the back-bearing computation which could be due to small-scale motions of the eddies and the bathymetry. The monthly RMS of the arrival angle, which captures this oscillation, is 0.16°. There are no internal waves in the simulation.

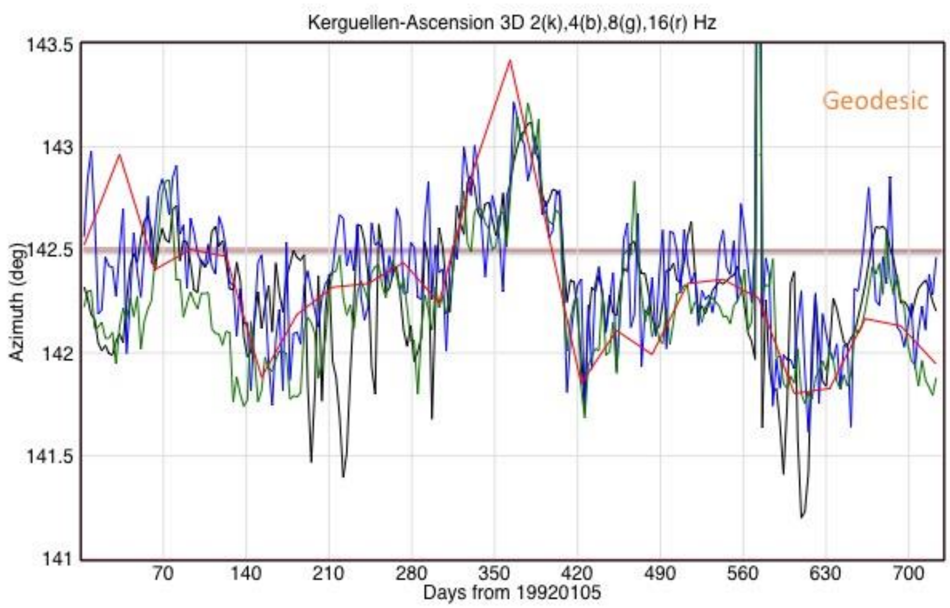

Figure 1. Centroid of arrival energy for 2-16 Hz over 1992-1993 Ecco2 model.

The deflection of basin-scale low-frequency acoustic propagation by mesoscale eddies and oceanic fronts was evaluated using a three-dimensional parabolic equation model. The 3D PE model Peregrine was introduced and applied to the simulated problem of the arrival of energy at the IMS station HA10S (Ascension) in the South Atlantic from an earthquake on the Kerguelen ridge in the south Indian Ocean. The field was computed for the World Ocean Atlas 2009 climatology and a two-year time series from the ECCO2 eddy-resolving re-analysis for the acoustic frequencies spanning 2 – 16 Hz. The back-azimuth was computed by beamforming on a roughly 13 km x 13 km two-dimension array centered near Ascension. The climatology ocean (WOA09) showed very little seasonal dependence or change from the geodesic and this is presumed to be due to the smoothing of the front due to the spatial and temporal averaging process of building the climatology. The ECCO2 results, on the other hand showed a deviation of back-azimuth ranging over a range of nearly 2° over the two year period. The back-azimuth was consistent across the frequency band and showed a 120-day "seasonal" oscillation.

The results presented here are consistent with the Munk's[1] prediction of an order of magnitude of 1° deflection. They are larger than the observations made by Voronovich *et.al.*[2] *(*RMS ~ 0.36°) and numerical results of Dushaw[3] (~0.2°), which can be explained by the larger propagation distance and the more dynamic Agulhas retroflection region compared to the North Eastern Pacific.

Dushaw's conclusion was that horizontal refraction has a negligible impact on ocean acoustic tomography and regional submarine source localization. For global scale seismic or nuclear event detection, however, this effect can be significant. The implications of a 1° error in back-azimuth for localization are significant for propagation at basin scale ranges (9100 km for this case). A simpler $\Delta\theta$ calculation for a bearing error of 1° yields a position offset of 158 km for this example. The impact of this is illustrated in Figure 2 where the geodesic connecting the source / receiver and the back-azimuth line are plotted overlaid on the 3D depth averaged Transmission Loss result.

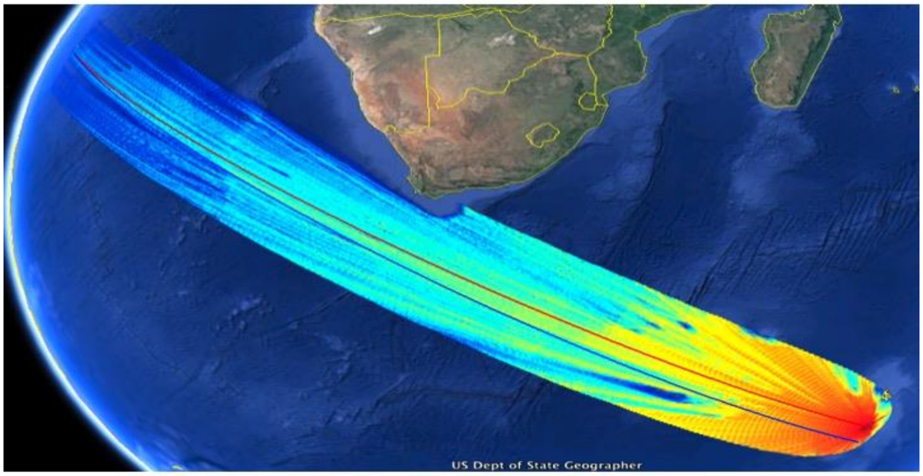

Figure 2. Localization error (southern line) using back-azimuth compared with source-receiver geodesic (northern line) overlaid on the 4Hz 3-dimensional acoustic field (color online)

In addition to examination of mesoscale refraction, work was undertaken this quarter to model very long range propagation from explosive shots.

Dr. Heaney worked with Dr. Mario Zampolli, including a visit to CTBTO in Vienna, to discuss recordings on the CTBTO network of the 200/400 kg explosive shots detonated by Dr. Tomoaki Yamada of University of Tokyo 800 km east of Japan. These recordings were received at Wake Island (North and South) at a range of 4500 km and at the Juan Fernandez station (North and South) at a range of 19000 km. This is an incredible data set as the source shot times and locations were recorded as were the source levels using a monitor hydrophone. The "short" range signals show evidence of a reflection off of the Island of Japan at 950s behind the direct signal. The "long" range recordings have some shots with adequate SNR and others are blocked, ostensibly the Hawaiian Island Chain. The physics mechanisms being investigated include:

- How does sound couple to the deep SOFAR (Sound Fixing and Rangin) channel for very long range propagation?
- How do islands between source/receiver block the propagation - how much 3D diffraction occurs to fill in the shadow zone behind the islands?
- What is the long-range arrival time and structure of the signal?
- Can we identify the late arriving energy, echoing off of distant seamounts?
- Can we use 3D acoustics to improve the source localization algorithms?
- Can we measure the Transmission Loss and infer something about the volume attenuation and therefore the pH of the ocean from the North Pacific to the polar South Atlantic?

Examples of the recorded pulse at Wake Island are shown in Figure 3.

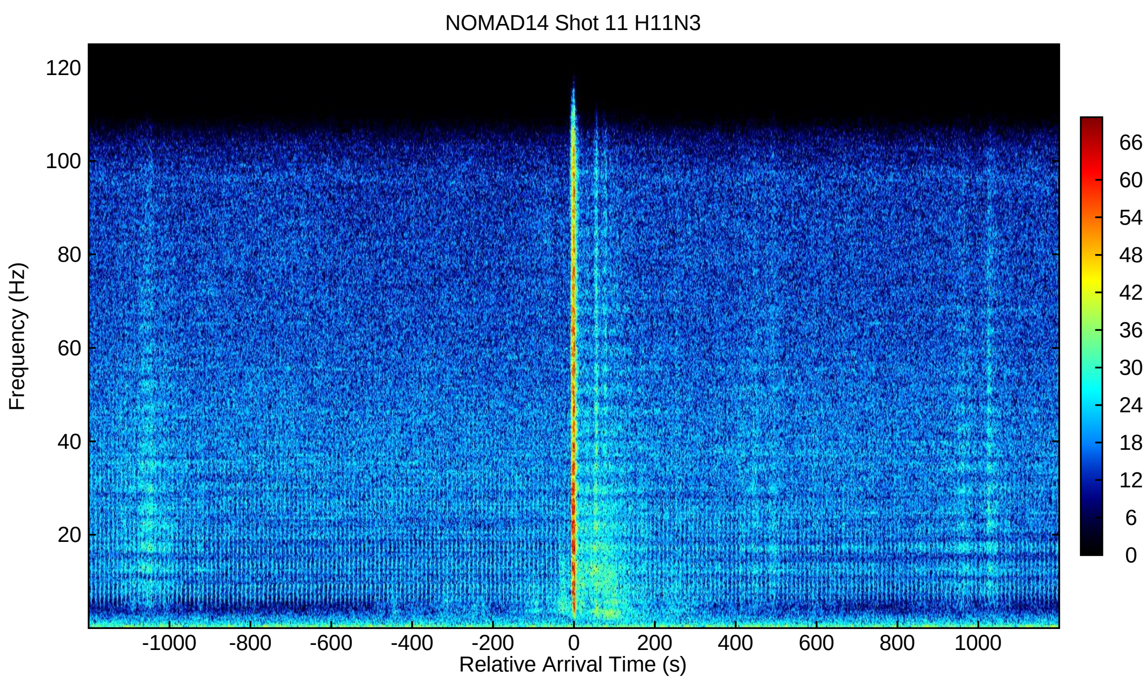

Figure 3. Spectrogram of pulse recording at Wake Island North of the 200 kg NOMAD explosive shot 11. The propagation range is ~4500 km. Note there are echoes at 40s and ~ 1000 s after the shot arrives.

A few of the signals have very strong arrivals at Juan Fernandez off the coast of Chile. One of these is shown in Figure 4.

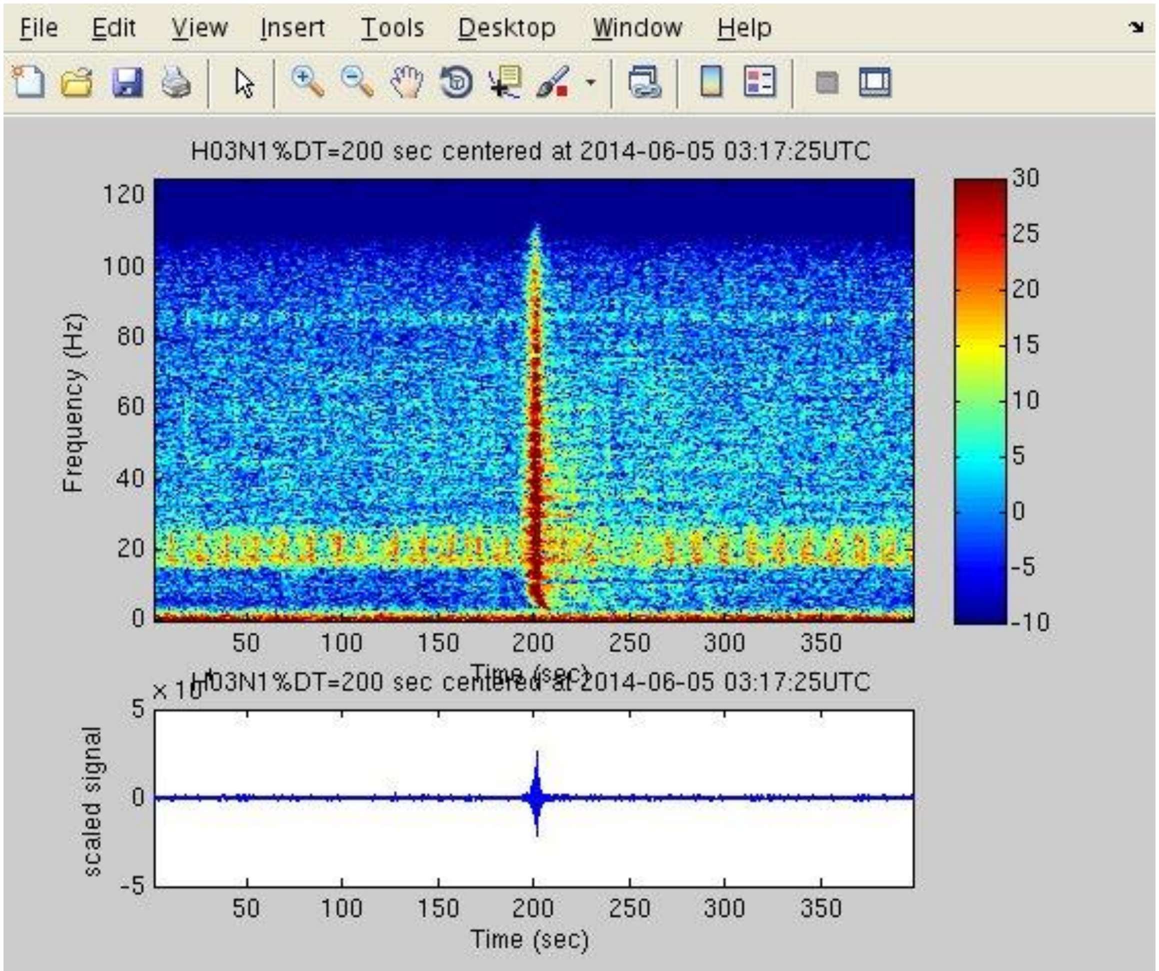

Figure 4. Spectrogram and time series of pulse recording at Juan Fernandez (Chile) North3 of the 200 kg NOMAD explosive. The propagation range is ~19000 km.

b. Task 2: NPAL PhilSeal0 Data Analysis and Matched Field Processing

During the Philippine Sea 2010 experiment, Dr. Peter Worcester (SIO) deployed a large full-water column spanning vertical line array and Dr. Heaney and Prof. Baggeroer (MIT) deployed a source to transmit waveforms to the array. One of the more interesting results to date is the evidence of strong narrowband interference patterns in the data with depth as the source was towed within 1-CZ of the array. These are shown in Figure 5.

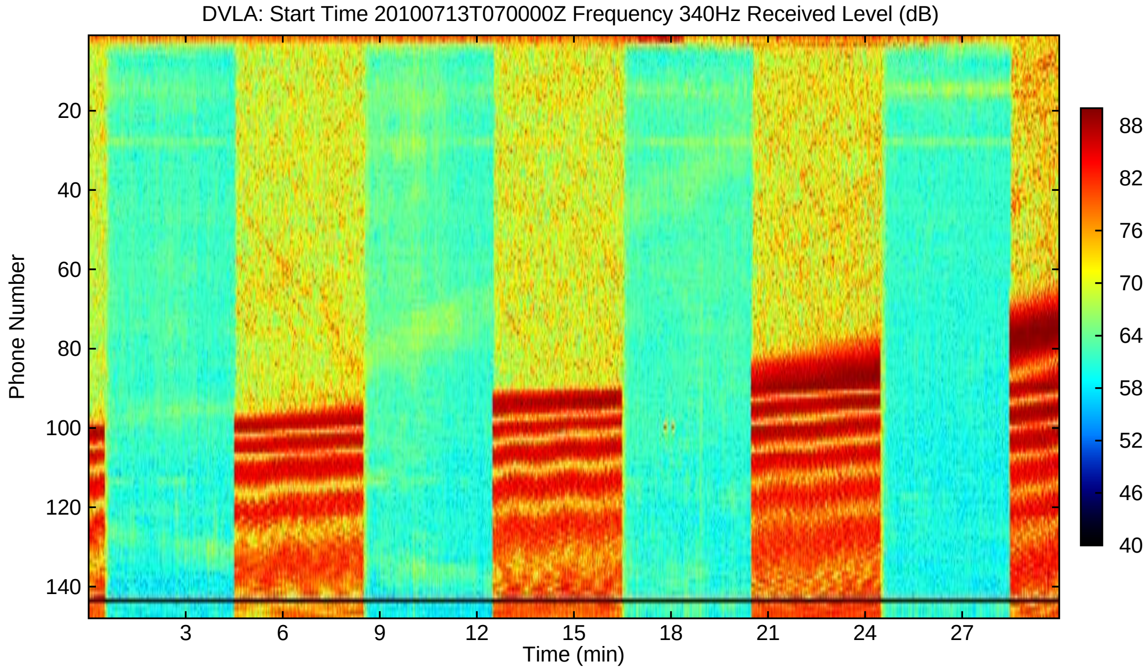

Figure 5. Narrowband (340Hz) received level vs. Phone Number (similar to depth) as function of time as the source moved from 10-20 km away.

The structure of this interference pattern is significant, even if it should not be surprising. This is the Lloyd's mirror pattern from the coherent surface reflection, after it has refracted from near the surface to depth. The reason that it is significant is that the behavior (spacing and change of spacing with time) can be used to estimate the source depth (only submerged sources have Lloyd's mirror patterns) and the source receiver-receiver range. This is evidenced in the Parabolic Equation model run for the same environment shown in Figure 6.

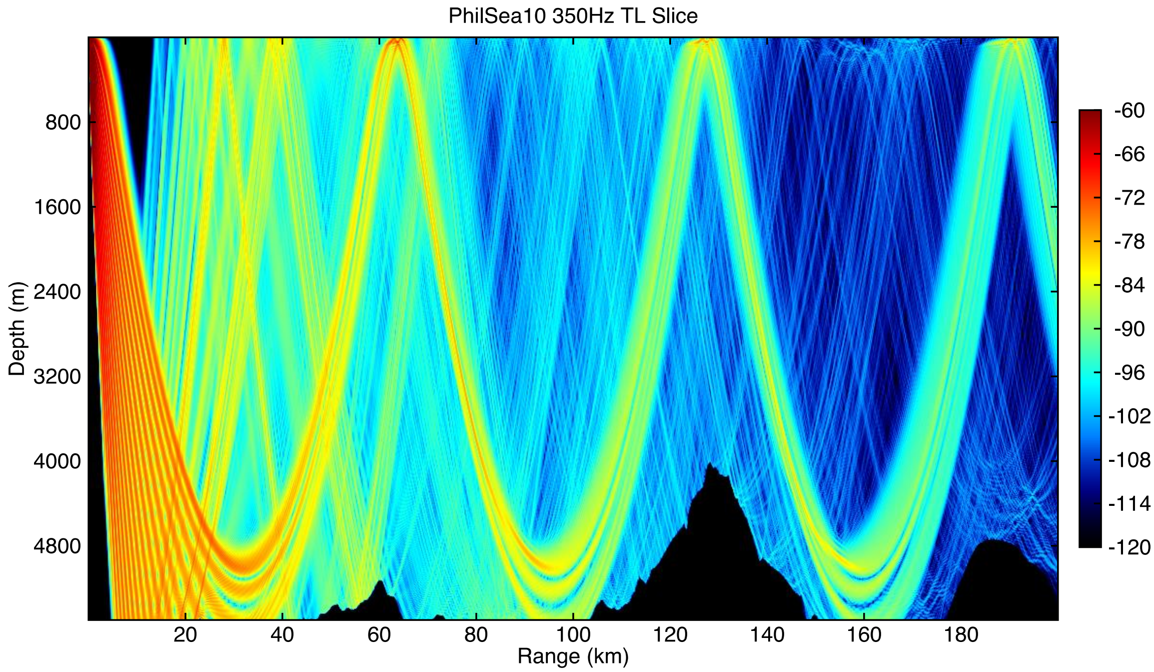

Figure 6. Narrowband (340Hz) Transmission Loss showing the refraction of the Lloyd's mirror pattern. This explains the strong interference pattern observed on the PS10 DVLA when the source was at ranges of 20-30 km.

The interference pattern, shown in Figure 7 is from a Star-of-David maneuver when the source/receiver range oscillated from 25-35 km as the R/V Revelle moved clockwise around the PS10 location.

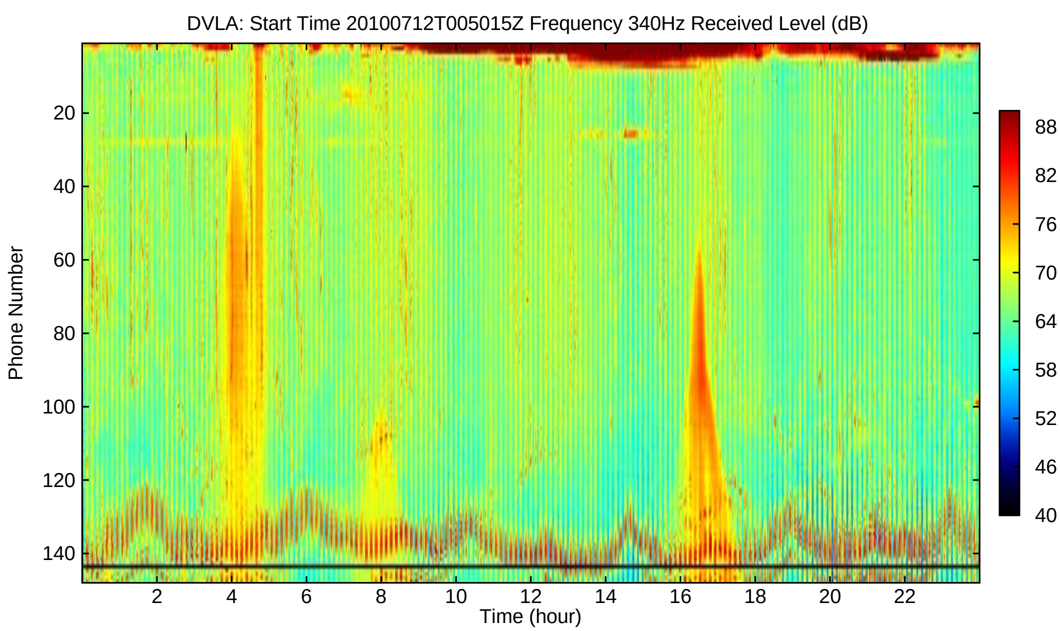

Figure 7. 24 Hour Narrowband source receiver level showing the deep refracted signals at exactly ½ CZ, or the RAP range.

When the ship closed on the DVLA, the direct path arrivals move up the array (as the source/receiver range shortens in Figure 6. The interference pattern of the surface reflected path is still visible. In Figures 8 and 9 the 110 and 340 Hz narrowband signals are plotted.

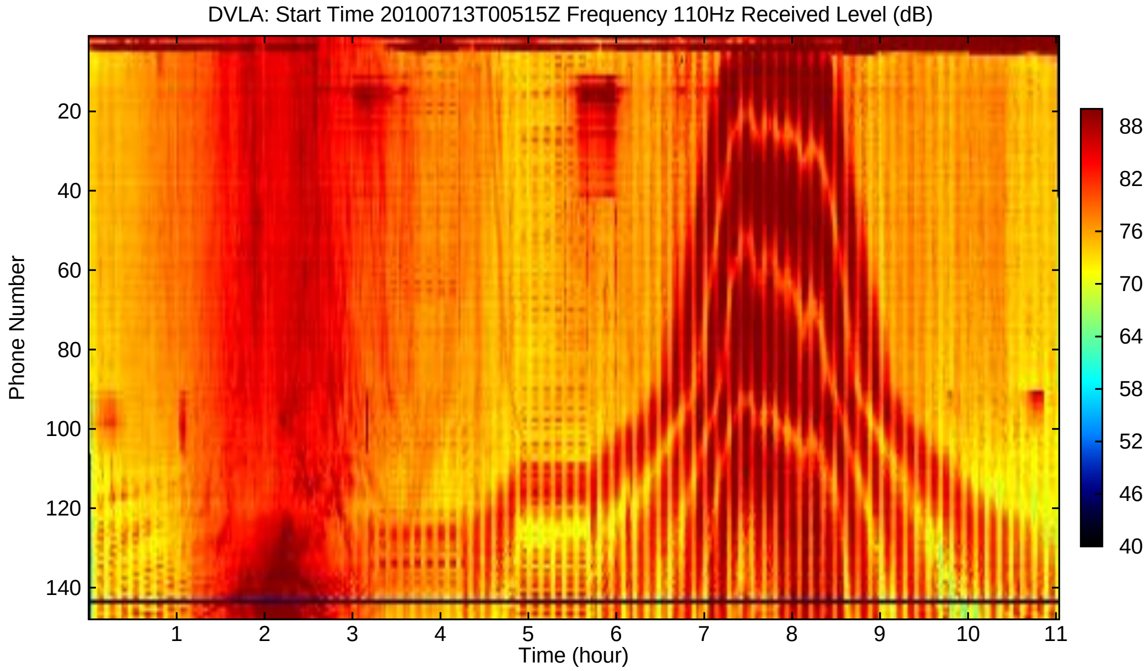

Figure 8. 11 Hour 110Hz Narrowband source receiver level showing the deep refracted signals as the ship approaches and passes CPA.

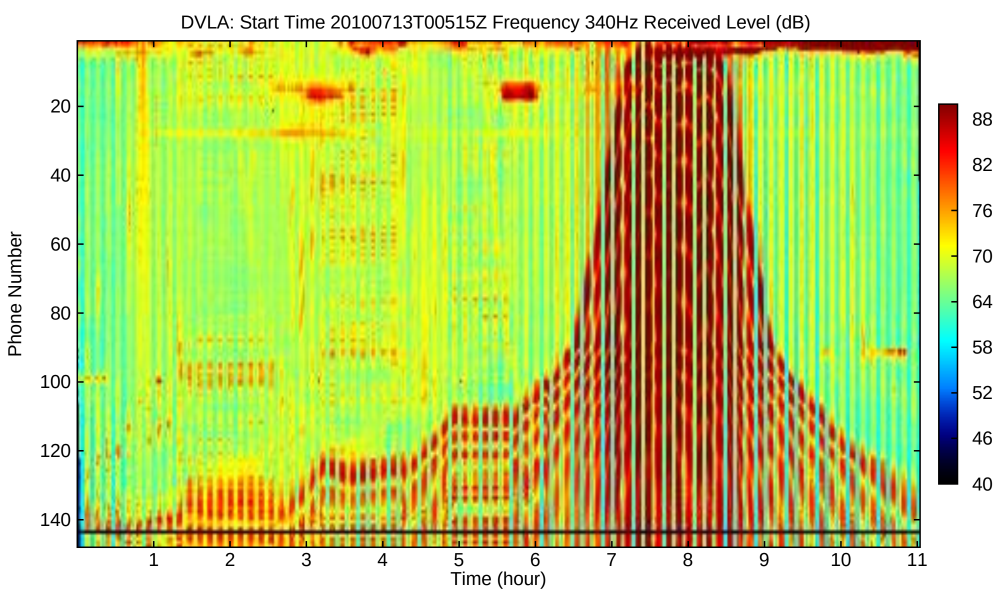

Figure 9. 11 Hour 340Hz Narrowband source receiver level showing the deep refracted signals as the ship approaches and passes CPA.

The presence and behavior of these interference patterns are completely predictable (up to moderate sea-states) and can be used as a target classification (submerged/surface) and ranging tool, even for single deep hydrophone receivers, such as the NOGAPS system. Dr. Heaney and his team will be investigating the possibilities of autonomous classification and ranging in the near future.

3. Future Plans

For the next quarter, the focus of the work will be on examining measurements and models of the 3-dimensional diffraction induced by bathymetric scattering. Observations have been made from the CTBTO hydroacoustic stations of seismic events that are in the acoustic shadow due to island (or continent) blockage. The 3D Peregrine model will be applied to these examples demonstrating that diffraction can explain the observations of hydroacoustic signals in the deep shadow.

The impact of bathymetric diffraction on the global coverage of the CTBTO network will be evaluated. Early computations indicate that the filling in from bathymetric diffraction can be on the order of 3% of the earth's globe, for a single station, which corresponds to 15 million km^2.

4. Publications and Peer Interactions

Dr. Heaney presented at the CTBTO Hydroacoustics workshop, Vienna July 2015, a paper entitled "Advanced computation of three-dimensional long-range acoustic propagation for improved localisation methods"

Dr. Heaney visited Emanuel Coelho at CMRE in La Spezia Italy and Peter Worcester/Bill Kuperman at Scripps Institution of Oceanography. Dr. Heaney presented a global acoustic seminar at the Applied Ocean Sciences Seminar at Scripps.

Dr. Heaney has submitted the paper "Three-dimensional parabolic equation modeling of mesoscale eddy deflection" to JASA.

5. References

1 Walter Munk, "Horizontal deflection of acoustic paths by mesoscale eddies," Journal of Physical Oceanography **10**, 596-604 (1980).

2 Alexander G. Voronovich, V. E. Ostashev, The NPAL Group, J. A. Colosi, B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, Walter Munk, R. Spindel, and P. F. Worcester, "Horizontal Refraction of acoustic signals retrieved from North Pacific Acoustic Laboratory billboard array data," Journal of the Acoustical Society of America **117**, 1527-1537 (2005).

3 Brian D. Dushaw, "Assessing the horizontal refraction of ocean acoustic tomography signals using high-resolution ocean state estimates," The Journal of the Acoustical Society of America **136** (1), 122-129 (2014).

Financial Summary

OASIS, INC.
JOB STATUS REPORT **9/30/2015**

1172 DEEP WATER ACOUSTICS **N00014-114-C-0172**
POP: 9/27/13-3/6/16

CONTRACT VALUE	Cost	Fee	Total
Contract Value	$368,935	$27,048	$395,983
Funding Value:	**$215,404**	**$15,791**	**$231,195**
Remaining to Fund:	$153,531	$11,257	$164,788

CUMULATIVE SPENDING WITH COMMITMENTS

	DIRECT	OH	MH	TOTL COST	FEE	**TOTAL**
ACTUAL						
OASIS	$97,073	$75,481	$1,903.00	$174,457	$13,084	**$187,542**
COMMITTED						
	$0	$0	$0	$0	$0	**$0**
	$97,073	$75,481	$1,903	$174,457	$13,084	**$187,542**
TOTAL REMAINING TO SPEND:						**$43,653**